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Development of Lightweight Radiators for Lunar Based Power Systems

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Space Administration

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ABSTRACT

This report discusses application of a new lightweight carbon-carbon (C-C) space radiator technology developed under the NASA Civil Space Technology Initiative (CSTI) High Capacity Power Program to a 20 kW_e lunar based power system. This system comprises a nuclear (SP-100 derivative) heat source, a Closed Brayton Cycle (CBC) power conversion unit with heat rejection by means of a plane radiator. The new radiator concept is based on a C-C composite heat pipe with integrally woven fins and a thin walled metallic liner for containment of the working fluid. Using measured areal specific mass values (1.5 kg/m^2) for flat plate radiators, comparative CBC power system mass and performance calculations show significant advantages if conventional heat pipes for space radiators are replaced by the new C-C heat pipe technology.

INTRODUCTION

Ever since the first lunar landing almost 25 years ago, establishment of a permanent lunar presence by humans has been an intriguing concept. Establishment of lunar outposts, bases or even lunar colonies has been the topic of numerous studies as exemplified in references 1 to 4. Lunar bases would represent strategic assets for development and testing of space technologies required for further exploration of the solar system. Technologies culminating in utilization of lunar resources would enable even more ambitious projects, such as construction of optical and radio astronomy facilities. Besides the tremendous benefits resulting from the absence of radio interference on the lunar far side, operation of a lunar radio telescope as an element of a "Very Large Baseline Array" (VLBA) which includes earth based telescopes a separation distance some thirty times wider than the maximum possible separation on earth would be possible. Since telescope resolving power is determined by the ratio of wavelength to baseline separation distance, resolutions could then approach values of less than 10^{-5} arc seconds at centimeter scale wavelengths, permitting detailed observations on disks of nearby solar size stars [5].

A key prerequisite for the establishment of a lunar outpost is a reliable power system to supply the energy requirements for science, life support, and operational activities. Since such a power system should provide continuous output throughout the 29.5 day synodic month, half of which (354 hours) receives no sunlight, the advantage of a sun independent heat source is obvious. Several studies have been performed on using the lunar soil (regolith) as a thermal energy storage material in conjunction with a solar power system. A conclusion reached [3] was that while thermal energy could be stored as relatively low temperature sensible heat, high temperature latent heat storage required for a viable solar dynamic power system would require an elaborate heat distribution and retrieval system, technologically so complex, that the concept was judged to be impractical.

To overcome the problems associated with the energy storage requirements associated with solar power systems for lunar applications power plants with nuclear heat sources offer definite advantages. With the energy source being truly independent of insolation, no energy storage would be required and the overall system mass requirement would be far lower. Moreover, the reactor shielding problem would be greatly simplified by taking effective advantage of the local crater topography and the use of indigenous lunar regolith materials. An application of the nuclear reactor technology being developed under the SP-100 program was proposed [4], utilizing a "Free Piston Stirling" power conversion system with linear alternator produced power output. This concept was based on the 2.5 MW_t fast spectrum lithium cooled reactor supplying heat at 1300 K to 8 modular Stirling engines. Maximum power output was rated at 825 kW_e. For this concept the reactor was located in a 4 m deep cylindrical excavation, requiring less than 40 m^3 of lunar soil to be removed. The power system proposed here also uses a nuclear heat source. But since the nominal output power level is only 20 kW_e the reactor thermal power requirement is lower by more than an order of magnitude. Consequently the shielding requirements are even lower than those for the system cited above. The power conversion system is based on the Closed Cycle Gas Turbine (CCGT), also referred to as the CBC, that had been developed [6] for the initial configuration of the space station "Freedom" and also proposed for a demonstration of scaled

down SP-100 reactor coupled to a CBC [7] to meet the power requirements of an interplanetary electric propulsion mission. The power system benefits resulting from the use of a light-weight C-C radiator in the lunar day/night temperature environment will be explored in the succeeding sections.

LIGHTWEIGHT C-C RADIATOR DEVELOPMENT

Development of this technology was conducted under an "Advanced Radiator Concepts" (ARC) contract between the NASA Lewis Research Center and Rockwell International Co. as a major effort of the Civil Space Technology (CSTI) Thermal management program [8]. As indicated in figure 1 (a), the basic element of a C-C radiator is a carbon-carbon heat pipe consisting of a tubular C-C pressure shell with integrally woven fins and a thin walled (0.064 mm) metallic liner of niobium-zirconium alloy which has been furnace brazed to the inner surface of the composite shell for containment of the heat pipe working fluid. A short extension of this liner protruding beyond one end of the shell forms the evaporator section which is in thermal contact with the power system radiator working fluid. The wall thickness for the evaporator and the two end caps is about 0.4 mm, permitting a structurally rigid radiator panel assembly. The surface emissivity of the C-C shell and fins was 0.85. Further details on the fabrication and assembly of the heat pipe, using the originally available T-300 C-C composite for the finned shell have been reported previously [9,10]. A 35 cm long heat pipe with 2.5 cm wide fins was successfully tested [11], starting from room temperature with the potassium working fluid in the frozen state to temperatures near 700 K. Figure 1 (b) shows a sketch of the instrumented test article.

Since the axial thermal conductivity of the heat pipe tested was limited to a maximum of 80 W/m-K, an additional task was added to the contract, to study methods of fabricating the woven preform finned shells using higher conductivity fiber yarn which is more difficult to weave. Several lengths of P-95 WG composite shells were successfully fabricated under this task. Since the conductivity of this composite was about 300 W/m-K at the targeted operating temperature of 800 K (equivalent to the SP-100 thermoelectric power system heat rejection temperature), the fin length (root-to-tip dimension) was increased from 2.5 to 5 cm, without any loss in fin efficiency. A comparison of the two fin designs and a detailed heat pipe component weight breakdown is given in Table 1, which shows that the long finned P-95 WG heat pipe achieves a 69 percent increase in radiating area at a mere 15 percent increase in mass. As a result the areal specific mass decreases from 2.1 to 1.45 kg/m^2. The heat rejection capacity as function

of temperature for the two C-C composites, figure 2, shows that the higher conductivity P95 WG composite heat pipe is capable of rejecting over 50 percent more heat than the T-300 composite, due to the higher radiating area.

LUNAR ENVIRONMENT

The lunar environmental sink temperatures over the synodic month period from full moon to the next full moon are shown in figure 3 (a). Using the Stefan-Boltzmann law, these equilibrium temperatures can be computed from a balance of direct solar heat absorbed and low temperature infra-red heat emitted, given surface emissivity (ϵ) and absorptivity (α) values. The relationship is given in equation 1 as:

$$T_e = ((\alpha/\epsilon) \times (L/4\pi\sigma d^2))^{.25} \tag{1}$$

where

T_e is the equilibrium surface temperature in K

$L = 3.9 \times 10^{26}$ W is the solar luminosity

$\sigma = 5.67 \times 10^{-8}$ W/m^{2}K^4 is the Stefan-Boltzmann constant

$d = 1.496 \times 10^{11}$ m, the average sun-to-lunar orbit distance

To calculate the equilibrium surface temperatures from lunar noon to midnight, the (α/ϵ) ratio was varied from 0.93 to .003, assuming the power system site to be located near the lunar equator. Radiatively coupling the lunar sky temperatures with the temperature profile shown, a mean effective daytime sink temperature of 360 K and an effective night-time temperature of 90 K was arrived at for power system heat rejection calculations. An interesting result was arrived at if the α/ϵ ratio was allowed to drop to 0.1, a condition which could be easily obtained by locating a vertical radiator centrally in an area that is covered by a highly reflective aluminized blanket. Since this blanket cover would be very thin (near 0.05 mm), its mass would be less than 0.1 kg/m^2. Figure 3(b) shows that for a radiator height of 1 meter a cover width of about 6 meters on each side would be sufficient to lower the daytime effective sink temperature to about 230 K. Also shown in figure 3(b) that the equivalent sink temperature for a horizontal radiator would be near 340 K for the lunar noon insolation. Figure 3 (c) shows a simple implementation of a power system with a radiator utilizing an aluminized reflective cover.

These results have significant effects on lunar power cycle calculations as discussed in the next paragraphs.

CLOSED CYCLE GAS TURBINE (CCGT) POWER SYSTEM

Coupling of a reactor heat source to a CCGT, also referred to as a "Closed Brayton Cycle" (CBC), has been studied in the mid sixties [12,13], especially for high power levels for terrestrial power plants utilizing high temperature gas reactors. The present study utilized an updated version of the CBC system described in [7] as shown in figure 4. The main change was to raise the turbine inlet temperature to 1350 K by inserting a 90 percent effectiveness Li-He/Xe heat exchanger between the reactor and the power system loop. Also, besides replacing the aluminum honeycomb pumped loop radiator by the C-C composite heat pipe design, the heat rejection subsystem was simplified by allowing direct heat transfer between the CBC working fluid and the heat pipe evaporators, rather than use an intermediate gas-liquid heat exchanger. The CBC working fluid was the same He/Xe mixture with a molecular weight of 83.8. The radial compressor and turbine diameters were kept at 0.106 m and .15 m, respectively, and the design speed was maintained at 36 000 rpm. Compressor and turbine efficiencies were computed for the proper pressure ratios on the basis of 0.85 infinitesimal stage efficiency. The alternator, located on the same shaft, designed to generate current at 1.2 khz, accomplishes nearly an order of magnitude mass reduction, compared to a generator producing 60 hz. A detailed component mass breakdown for the reference system is shown in table 2.

POWER SYSTEM DESIGN STUDIES - Using an existing CBC power system mass optimization code developed by the author, performance and system mass computations were carried out under four sets of input conditions as indicated in columns 1 to 4 of table 3. The information contained in these columns permits performance and overall system mass comparisons between a system operating during the lunar day, utilizing a traditional flat plate radiator having a specific mass of 5 kg/m^2, to a system using the C-C composite radiator (specific mass of 1.5 kg/m^2) operating in the following lunar environments: daytime (column 2), night-time (column 3), and daytime with a reflective aluminized mylar blanket covering an area adjacent to the radiator, as discussed above. The mass optimizations resulted in four different power system designs as can be observed from the system parameters shown in the four columns. For simplicity, the highlighted key parameters of: cycle temperature ratio, thermal efficiency, sink temperature, radiator area, and system mass, give an essential description of these systems. Due to its heavier radiator material the system in column (1) is limited to a temperature ratio of 2.9, yielding an efficiency of 27 %, a radiator area of about 23 m^2, and an overall system mass of 1460 kg. Although not shown in the table, a doubling of radiator specific mass to 10 kg/m^2 would have lowered the efficiency to 23 % and raised the

system mass to 1600 kg.

Column (2) shows that with the lighter C-C radiator the temperature ratio could be increased to 3.2, resulting in a thermal efficiency over 32 %, a radiator area of 30 m^2, and an overall system mass of only 1351 kg. Lunar night operation and use of a reflective cover (columns 3 & 4) results in efficiencies of over 43.3 % and 40.6 %, respectively. Note that the overall system masses for the two conditions differ by less than 10 kg. Even after allowing for the additional mass of the blanket (about 10 kg for 120 m^2), the strategic value of this device is obvious. Of course, special care will have to be taken to prevent lunar dust from covering the blanket.

Having obtained the mass variations for systems designed specifically for the extremes in environmental conditions, we next investigated the performance of a single compromise system, table 4, at the same conditions, except for including a traditional radiator (column 1) for comparison. With a constant temperature ratio of 3.4, thermal efficiency is fixed near 35 %, with minor deviations due small variations in pressure ratio. Note the 175 kg mass savings resulting from replacement of the traditional with a C-C radiator of approximately 40 m^2 for the lunar midday condition. Also note that the CBC operating during the lunar night requires only about half the radiator area to produce the same power. Similarly, use of a reflective blanket reduces the radiator area requirement from 40 to 23 m^2 during daytime operation. The significance of these results is twofold:

(1) If a reflective blanket can be deployed around a lunar power system radiator the radiating area requirement for daytime operation can be reduced by 43 %.

(2) For lunar power systems designed to deliver rated output power during the lunar day without reliance on a reflective cover, the excess radiator area available during night time operation can be utilized to produce excess power for storage. This would also require reactor thermal power modulation, working fluid inventory control and alternator field adjustment.

EXTENSION OF RESULTS TO HIGHER POWER LEVELS

Second and third generation power systems to meet the energy demands of large lunar bases and colonies will eventually need to be designed with power outputs in the multi-megawatt range [1,2]. Since for such power levels the heat rejection subsystem can represent over 50 % of the total system mass, the use of lightweight C-C radiators would have an even greater impact on total mass than for the 20 kW$_e$ power system considered here. Reactor shielding requirements would also be reduced by locating the reactor below ground level [4]. Figure 5 shows how this strategy might be applied to

a second generation CBC power system, using flat C-C radiators. To assure high overall power system reliability several parallel redundant power conversion units (PCUs) could be used with a single high temperature gas reactor heat source, as proposed for nuclear electric propulsion [14] systems. Figure 6 shows such a conceptual power plant using eight parallel redundant Brayton PCU's, each with its own radiator panel. The resulting "spoked wheel" radiator configuration is located on a reflective cover. Note that even though the panels have a partial view of each other, the view factor to the space sink is only reduced by about ten percent, thus requiring only a modest increase in deployed radiator area to compensate for this effect.

CONCLUDING REMARKS

Although national priorities and present funding limitations have resulted in a postponement of programs requiring permanent lunar bases, the results of this and other studies and the analysis tools used should facilitate future work in this area. It was shown that lightweight C-C heat pipes developed under the NASA LeRC "Advanced Radiator Concepts" project can significantly reduce lunar power system radiator and overall system mass. This mass reduction becomes even more drastic for high power level systems.

Reflective blankets covering the surface adjacent to vertically deployed radiators lower the effective sink lunar day temperature thereby reducing radiator area requirements.

Nuclear power systems with radiators designed for lunar day operation can be designed to produce excess power during the lunar night.

Availability of a huge terrestrial technology data base, coupled with the non-hazardous inert gas working fluids should permit component development for space power applications at lower cost than for other candidate systems requiring testing with liquid metals at high temperatures.

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Table 1: Carbon-Carbon Heat Pipe Mass Breakdown

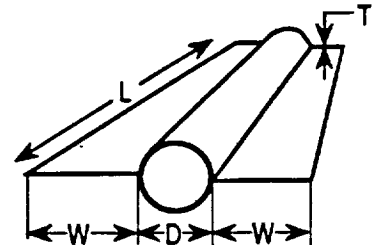| COMPONENT	T-300 Composite	P-95 WG Composite
DIMENSIONS (SEE SKETCH)	L = 91.4 cm; D = 2.5 cm W = 2.5 cm; T = 0.1 cm	L = 91.4 cm; D = 2.5 cm W = 5 cm; T = 0.1 cm
C-C SHELL	169.5	214.0
LINER W, EVAPORATOR	41.2	41.2
END CAPS	13.1	13.1
FILL TUBES	7.2	7.2
BRAZE	22.5	22.5
WICK	24.0	24.0
WORKING FLUID	13.5	13.5
TOTAL MASS (G)	291.0	335.5
TWO SIDED RADIATING AREA - m^2	0.1383	0.2335
SPECIFIC MASS - kg/m^2	2.1	1.45

Table 2: Brayton Power System Component Mass Breakdown

Component	Component Mass kg	Component Mass (Percent of Total)
Reactor	363	23.6
Instrument Shield	315	20.5
Source Heat Exchanger & Pump	210	13.7
Recuperator	100	6.6
Turboalternator	50	3.3
Instrumentation & Controls	80	5.2
Main Radiator	210	13.7
Auxiliary Radiators	66	4.3
Radiator Heat Exchanger & Structure	140	9.1
Total System Mass	1534	100.0

Table 3: Lunar 20 kWe CBC Minimum Power System Characteristics

Gas Turbine Cycle Parameters Column No.	Lunar Day Traditional Radiator 1	Lunar Day C - C Radiator 2	Lunar Night C - C Radiator 3	Lunar Night Reflective Cover C - C Radiator 4
Turbine Inlet Temperature - K	1350.00	1350.00	1350.00	1350.00
Cycle Temperature Ratio	2.90	3.20	4.20	3.90
Compressor Inlet Temperature - K	466.00	422.00	321.00	346.00
Compressor Pressure Ratio	2.00	2.00	2.39	2.28
Compressor Exit Temperature - K	643.00	586.00	483.00	509.00
Reactor HX Inlet Temperature - K	1068.00	1062.00	1000.00	1017.00
Loop He/Xe Flowrate - kg/sec	1.04	0.86	0.53	0.59
Cycle Pressure Loss Parameter	0.94	0.94	0.94	0.94
Recuperator Effectiveness	0.95	0.95	0.95	0.95
Cycle Thermal Efficiency - %	27.10	32.24	43.30	40.60
Cycle Heat Rejected - kWt	53.80	42.00	26.20	29.30
Radiator Duct Inlet Temperature - K	666.00	611.00	510.00	536.00
Radiator Duct Exit Temperature - K	466.00	422.00	321.00	346.00
Effective Radiator Temperature - K	524.00	475.00	384.00	406.00
Space Sink Temperature - K	360.00	360.00	90.00	230.00
Main Radiator Area - m^2	22.77	30.40	29.20	29.10
System Specific Power - W/kg	13.71	14.81	15.24	15.20
System Specific Mass - kg/kW	72.95	67.54	65.60	66.00
Total System Mass - kg	1459.00	1351.00	1312.00	1319.00

Table 4: Lunar 20 kWe CBC Selected Power System Characteristics and Performance

| Gas Turbine Cycle Parameters Column No.	Lunar Day Traditional Radiator 1	Lunar Day C - C Radiator 2	Lunar Night C - C Radiator 3	Lunar Night Reflective Cover C - C Radiator 4
Turbine Inlet Temperature - K	1350.00	1350.00	1350.00	1350.00
Cycle Temperature Ratio	3.40	3.40	3.40	3.40
Compressor Inlet Temperature - K	397.00	397.00	397.00	397.00
Compressor Pressure Ratio	2.00	2.20	2.00	2.00
Compressor Exit Temperature - K	549.00	573.00	549.00	574.00
Reactor HX Inlet Temperature - K	1064.00	1035.00	1064.00	1032.00
Loop He/Xe Flowrate - kg/sec	0.79	0.73	0.79	0.78
Cycle Pressure Loss Parameter	0.94	0.94	0.94	0.94
Recuperator Effectiveness	0.95	0.95	0.95	0.95
Cycle Thermal Efficiency - %	35.10	34.60	35.30	35.20
Cycle Heat Rejected - kWt	37.00	37.80	36.70	36.80
Radiator Duct Inlet Temperature - K	576.00	597.00	576.00	578.00
Radiator Duct Exit Temperature - K	397.60	397.00	397.00	397.60
Effective Radiator Temperature - K	442.00	448.00	455.00	455.00
Space Sink Temperature - K	360.00	360.00	90.00	230.00
Main Radiator Area - m^2	41.74	39.60	21.00	22.60
System Specific Power - W/kg	13.10	14.73	15.13	15.10
System Specific Mass - kg/kW	76.64	67.90	66.10	66.20
Total System Mass - kg	1533.00	1358.00	1322.00	1325.00
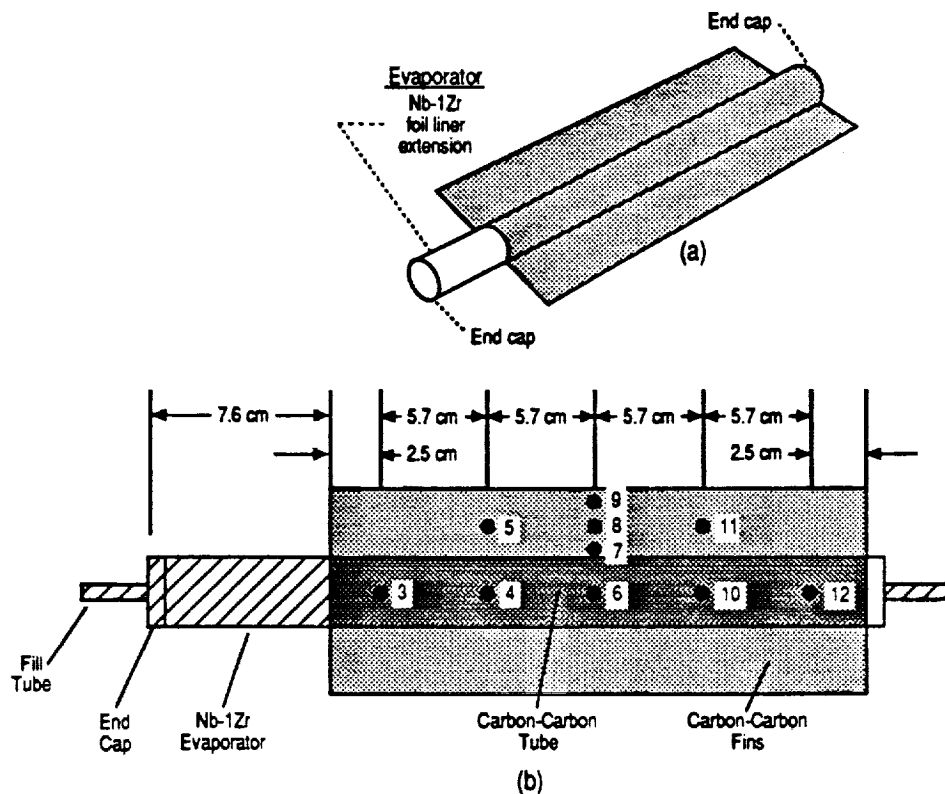
Figure 1: Carbon-Carbon Heat Pipe Radiator Element

(a) Sketch showing C-C shell and Metallic Liner/Evaporator Extension
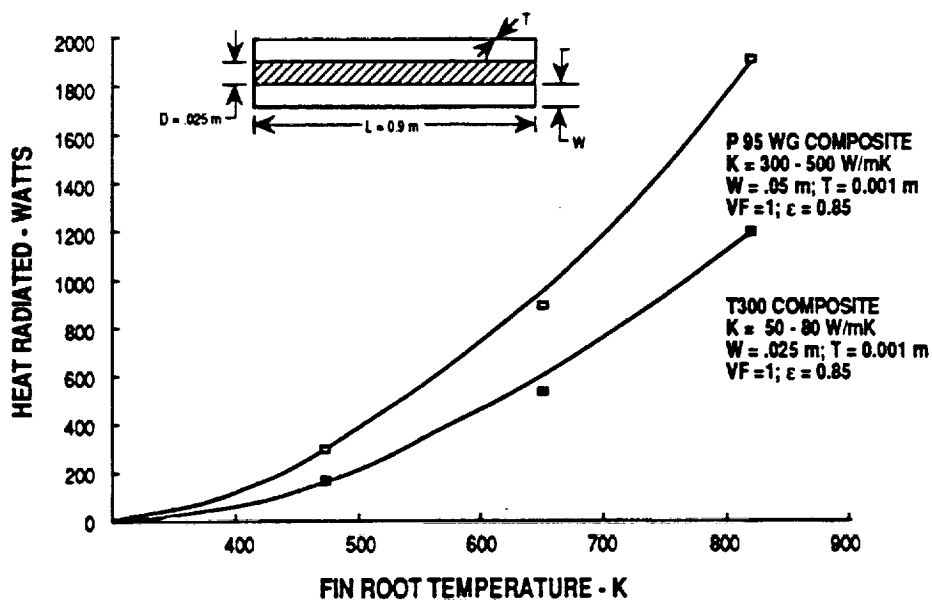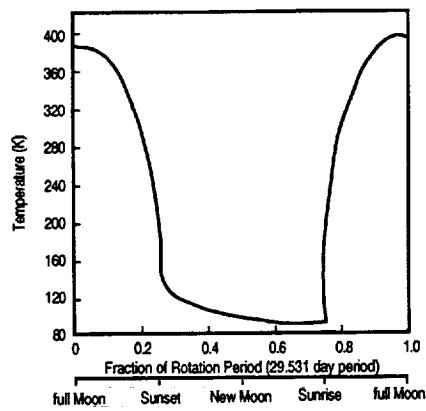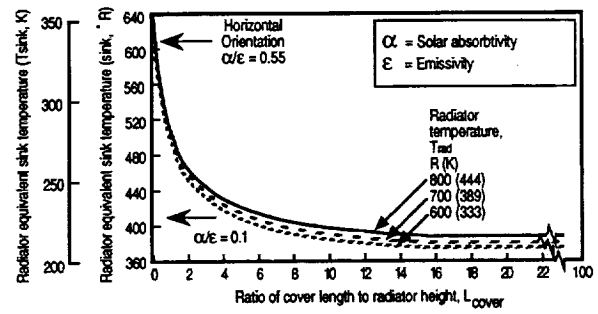
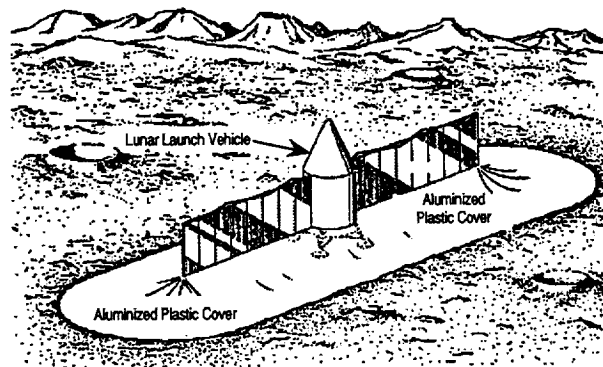(b) Test Article (top view) showing Thermocouple Locations

Figure 2: Thermal Conductivity Effect on Finned Heat Pipe Performance

Figure 3: Horizontal Orientation $\alpha/\varepsilon = 0.55$

α = Solar absorbtivity
ε = Emissivity

Radiator temperature, T$_{rad}$ R (K)
800 (444)
700 (389)
600 (333)

$\alpha/\varepsilon = 0.1$

Ratio of cover length to radiator height, L$_{cover}$

Radiator equivalent sink temperature (Tsink, K)

Radiator equivalent sink temperature (sink, R)

Temperature (K)

Fraction of Rotation Period (29.531 day period)

full Moon   Sunset   New Moon   Sunrise   full Moon

(a)

(b)

Lunar Launch Vehicle
Aluminized Plastic Cover
Aluminized Plastic Cover

(c)

Figure 3: Lunar Environment during Synodic Month

    a) Lunar Surface Temperature Variation
    b) Effect of Reflective Cover on Sink Temperature
    c) Lunar Outpost (Conceptual Sketch)

0.35 m²
Pump Radiator

NaK

Pump

0.25 kg/s

Main Radiator
42 m²

Gas Separator

1390 K

Lithium

1380 K

Reactor

Hot-Side Heat Exchanger

1350 K
742 kPa

Turbine

Alternator

Compressor

397 K
385 kPa

1090 K
395 kPa

549 K
770 kPa

1068 K

Recuperator

0.79 kg/s

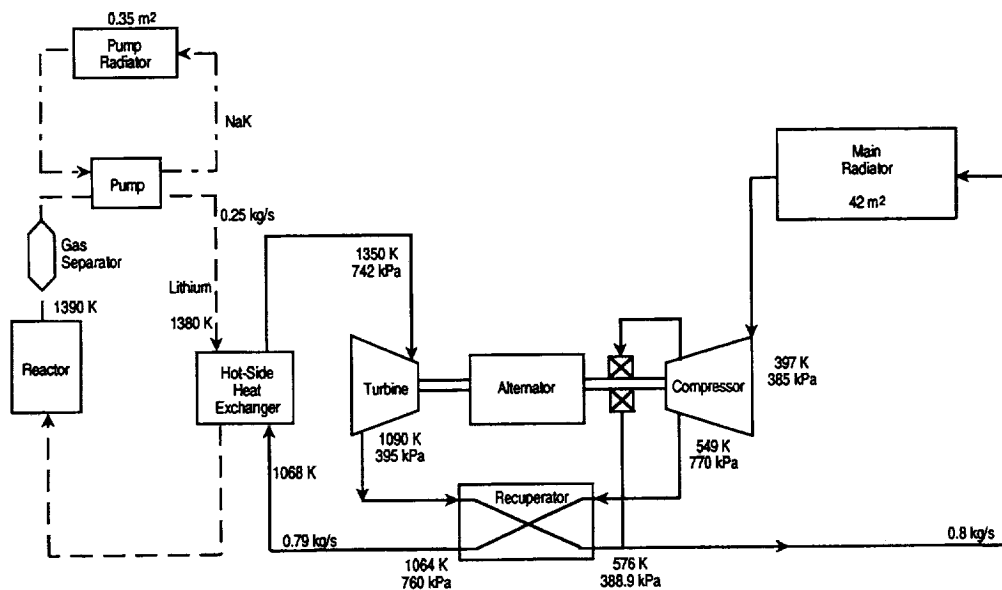1064 K
760 kPa

576 K
388.9 kPa

0.8 kg/s

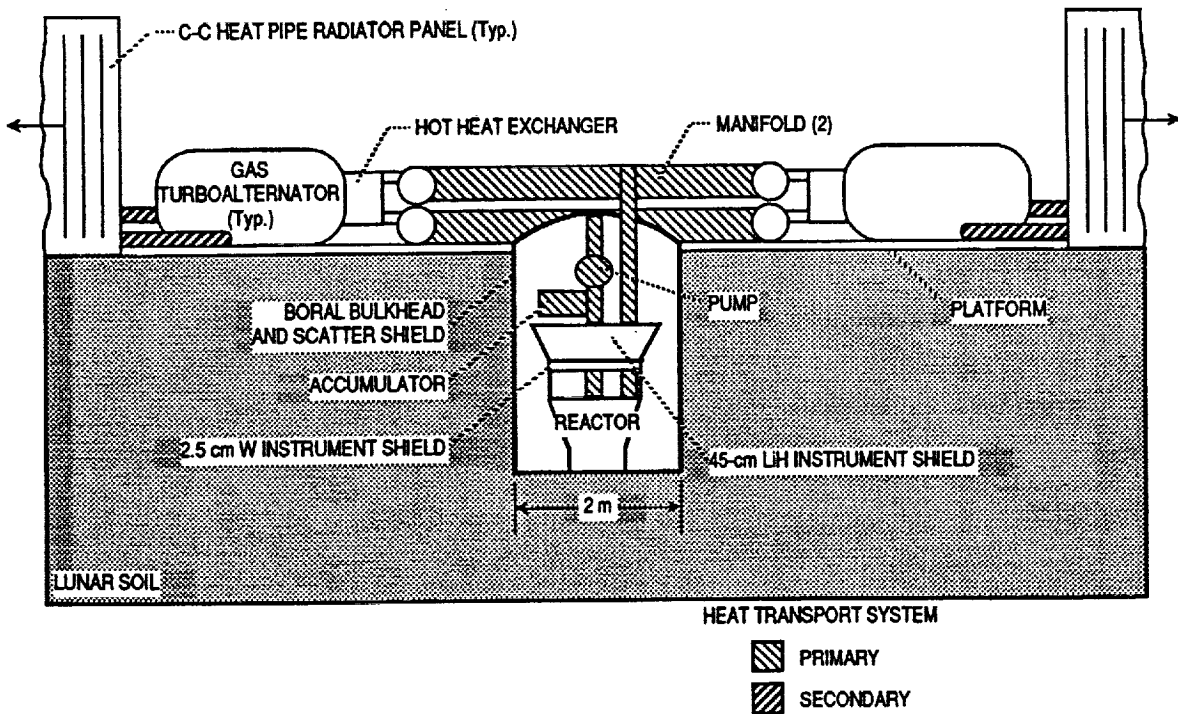Figure 4: Base Line Schematic for Lunar Power System

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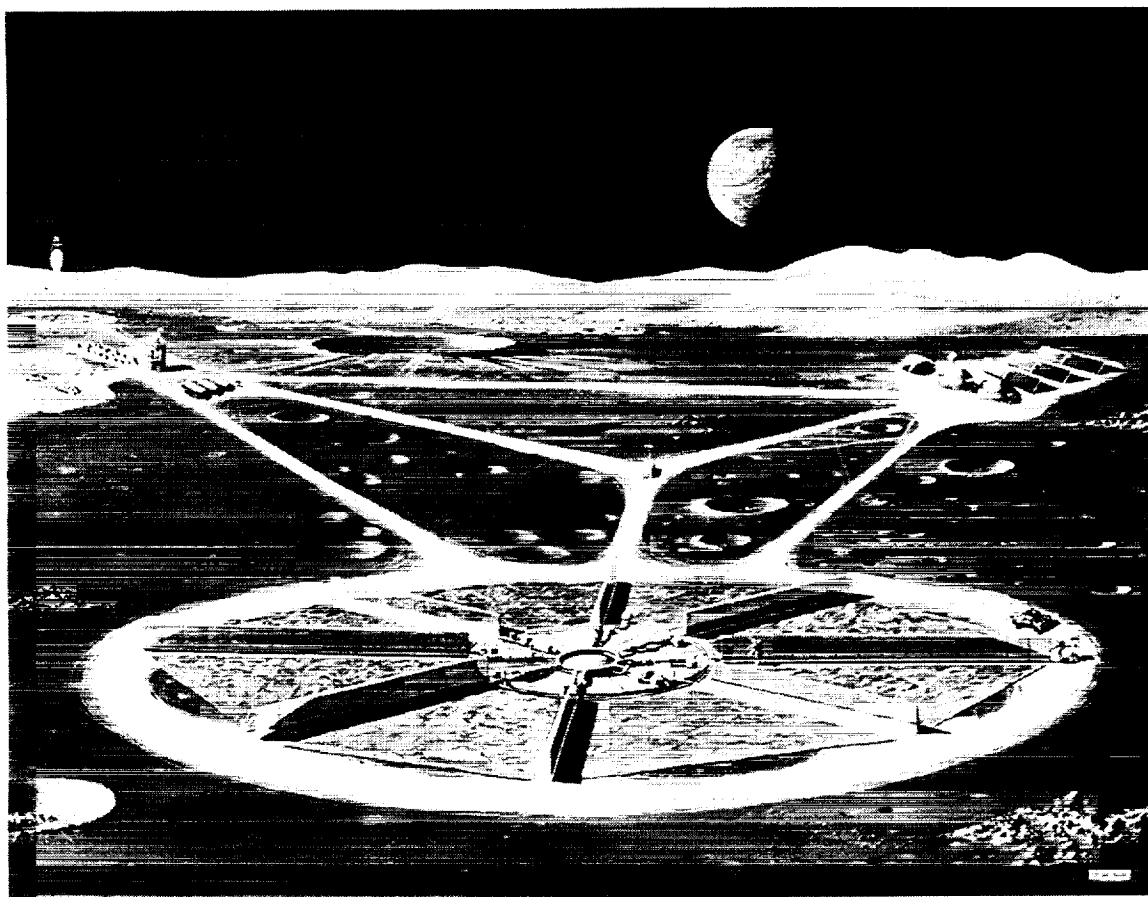Figure 5: Cutaway View of Second Generation Nuclear Power System for Lunar Base

Figure 6: Artist's rendering of Integrated Nuclear Power System for Megawatt Level Lunar Powerplant

REPORT DOCUMENTATION PAGE

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13. ABSTRACT (Maximum 200 words)

This report discusses application of a new lightweight carbon-carbon (C-C) space radiator technology developed under the NASA Civil-Space Technology Initiative (CSTI) High Capacity Power Program to a 20 kWe lunar based power system. This system comprises a nuclear (SP-100 derivative) heat source, a Closed Brayton Cycle (CBC) power conversion unit with heat rejection by means of a plane radiator. The new radiator concept is based on a C-C composite heat pipe with integrally woven fins and a thin walled metallic liner for containment of the working fluid. Using measured areal specific mass values (1.5 kg/m2) for flat plate radiators, comparative CBC power system mass and performance calculations show significant advantages if conventional heat pipes for space radiators are replaced by the new C-C heat pipe technology.

14. SUBJECT TERMS

Carbon-Carbon radiators; Space heat rejection; Lunar power system

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